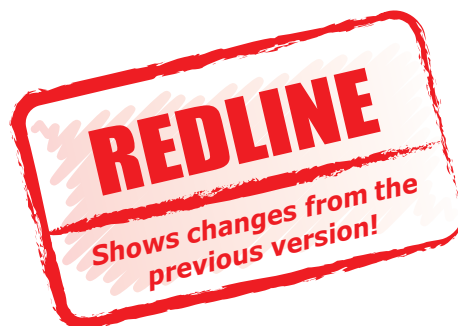


IEEE Guide for Investigation, Analysis, and Reporting of Power Circuit Breaker Failures

IEEE Power & Energy Society

Sponsored by the
Switchgear Committee



IEEE
3 Park Avenue
New York, NY 10016-5997
USA

30 December 2011

IEEE Std C37.10™-2011
(Revision of
IEEE Std C37.10-1995)

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IEEE Guide for Investigation, Analysis, and Reporting of Power Circuit Breaker Failures

Sponsor

Switchgear Committee
of the
IEEE Power & Energy Society

Approved 31 October 2011

IEEE-SA Standards Board

Abstract: Practices and processes to perform, analyze, and report failure investigations of power circuit breakers are provided.

Keywords: circuit breaker, circuit breaker failure analysis, circuit breaker failure guide, circuit breaker failure investigation, circuit breaker failure reporting, IEEE C37.10

The Institute of Electrical and Electronics Engineers, Inc.
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PDF: ISBN 978-0-7381-7144-9 STD97176
Print: ISBN 978-0-7381-7169-2 STDPD97176

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Introduction

This introduction is not part of IEEE Std C37.10-2011, IEEE Guide for Investigation, Analysis, and Reporting of Power Circuit Breaker Failures.

This guide is a revision to IEEE Std C37.10-1995 (Reaffirmed in 2002 and 2008). This guide also incorporates the previous IEEE Std 1325™-1996 (Reaffirmed in 2002 and 2008).

This issue of IEEE Std C37.10 has the following changes:

- Changed title from IEEE Std C37.10-1995
- Included failure reporting form from IEEE Std 1325-1996
- Added additional definitions
- Updated references
- Added a subclause on failure investigation preparedness
- Re-ordered and revised material to better align with the investigative process
- Added a url directing readers to an interactive reporting form that will be available from IEEE with the guide
- Added to the bibliography (The bibliography has the standards listed in chronological order with the intent to make it easier to correlate the appropriate standards with the date of the circuit breaker being investigated.)
- Added and consolidated safety considerations

Users of this guide are reminded to use the appropriate edition of the circuit breaker standards that apply to the circuit breaker being investigated.

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Contents

1. Overview	1
1.1 Scope	1
1.2 Purpose	1
1.3 Preparation and training.....	2
2. Normative references.....	2
3. Definitions	3
4. Procedure for investigation of circuit breaker failures	5
4.1 Determining the hazards and risks associated with the circuit breaker inspection	5
4.2 Classification of failures	7
4.3 Immediate action	7
4.4 On-site data collection (major failures)	8
4.5 Investigation	8
4.6 Investigation flow chart	9
4.7 Recommended plan of action	11
5. Diagnostic tests and advanced diagnostics	12
6. Data collection and data structure.....	21
6.1 General approach.....	21
6.2 Preparation.....	22
6.3 Immediate investigation.....	23
7. Failure report utilization	27
7.1 Failure report utilization—General.....	27
7.2 Failure report utilization—Circuit breaker user.....	27
7.3 Failure report utilization—Circuit breaker manufacturer	28
Annex A (informative) Failure reporting for power circuit breakers	30
Annex B (informative) Bibliography.....	33
B.1 Guides to reliability design/analysis	33
B.2 Failure investigation.....	33
B.3 Guides to failure reporting	33
B.4 Equipment failure statistics	34
B.5 Guides to equipment monitoring.....	34
B.6 Circuit breaker reference books	34
B.7 Circuit breaker tutorials	34
B.8 Circuit breaker standards—USA.....	35
B.9 Circuit breaker standards and technical reports—IEC	38
B.10 Switchgear standards—Canada.....	41
B.11 Other references	41
Annex C (informative) Circuit breaker design and construction	42
C.1 Overview.....	42
C.2 Purpose.....	42
C.3 Types of circuit breakers.....	42
C.4 Interruption mediums of circuit breakers	43
C.5 Mechanisms of circuit breakers	46

IEEE Guide for ~~Diagnostics and Failure~~ Investigation, Analysis, and Reporting of Power Circuit Breakers ~~Failures~~

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1. Overview

1.1 Scope

This guide ~~recommends procedures to be used~~ provides practices and processes to perform, analyze, and report failure investigations of power circuit breakers. ~~Although the procedure may be used for any circuit breaker, it is mainly focused on high-voltage ac power circuit breakers used on utility systems.~~

~~Recommendations are also made for monitoring circuit breaker functions as a means of diagnosing their suitability for service condition.~~

1.2 Purpose

The purpose of this guide is

- a) To provide ~~sufficient~~ guidelines and promote uniformity in the analysis of power circuit breaker failures
- b) To provide guidance for systematic and uniform data collection so that valuable ~~facts are~~ evidence is not lost or destroyed
- c) To provide a methodology by which the most probable cause of any particular circuit breaker failure may be determined
- d) To encourage cooperative efforts by users and manufacturers during failure analysis
- e) ~~to encourage consistency of nomenclature and compatibility with similar efforts by other organizations such as CIGRE (International Conference on Large Voltage Electric Systems), EEl (Edison Electric Institute), IEC (International Electrotechnical Commission), NEMA (National Electrical Manufacturers Association), and AEIC (Association of Edison Illuminating Companies).~~
To provide guidance for reporting failures for power circuit breakers

1.3 Preparation and training

The investigation of circuit breaker failures requires some preparation and training of personnel.

The importance of preserving evidence that will allow successful determination of the cause of the failure must be balanced with the needs for safety of restoration of service. An organization should recognize the sometimes competing goals of restoring electric service and determining the cause of the failure. It is important to declare the priorities, which may change during the course of the investigation.

Local or on-site personnel should be adequately trained to deal with immediate hazards, isolation, grounding etc. These personnel may not be in charge of the subsequent investigation of the failure. Therefore, an organization should decide well ahead of time who will be trained to perform the actions at the scene required to preserve evidence, as well as contacting the appropriate internal group who will organize or lead the formal investigation. There may be a separate protocol and level of detail for different levels of investigation, depending on the nature and initially perceived severity of the failure.

An overall corporate incident management plan with a plan to handle possible circuit breaker failure investigations is recommended.

Active and planned cooperation between the owner of the circuit breaker and the equipment manufacturer is highly encouraged and is almost certain to result in a more accurate assessment of the incident. Full sharing of information relative to the circuit breaker failure is essential to having a productive process that will lead to improvements in circuit breaker design, manufacture, application, operation, and maintenance.

1.3 Organization

~~This guide is divided into two main parts as follows:~~

~~Part I: Failure~~ investigation

~~Part II: Diagnostics~~

~~Annexes provide information on advanced diagnostics, diagnostic tests, and circuit breaker basic design and application~~

2. References

~~ANSI C37.06-1987, American National Standard for Switchgear AC High Voltage Circuit Breaker rated on a~~

~~Symmetrical Current Basis—Preferred Ratings And Related Required Capabilities.¹~~

~~ANSI C37.11-1979, American National Standard Requirements for Electrical Control for AC High Voltage Circuit~~

~~Breakers rated on a Symmetrical Current Basis or a Total Current Basis.~~

~~IEEE Std 100-1992, The New IEEE Standard Dictionary of Electrical and Electronics Terms (ANSI).²~~

~~IEEE Std 1325-1996, IEEE Recommended Practice for Reporting of Power Circuit Breaker Field Failures.³~~

~~IEEE Std C37.04-1979 (R1988), IEEE Standard Rating Structure for AC High Voltage Circuit Breakers rated on a~~

~~Symmetrical Basis (ANSI).~~

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For this guide, undated references refer to the most appropriate edition of the referenced document and that edition applies (including any amendments or corrigenda). The investigation of circuit breaker failures requires use of references that are appropriate to the time when the circuit breaker was designed, tested, and applied to the power system. Annex B lists some historic versions and editions of circuit breaker standards.

[IEEE Std C37.04™, IEEE Standard Rating Structure for AC High-Voltage Circuit Breakers.](#)^{1, 2}

[IEEE C37.06™, IEEE Standard for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis— Preferred Ratings and Related Required Capabilities for Voltages Above 1000 V.](#)

[ANSI C37.06.1™, American National Standard Guide for High-Voltage Circuit Breakers Rated on Symmetrical Current Basis Designated “Definite Purpose for Fast Transient Recovery Voltage Rise Times”.](#)³

IEEE Std C37.09-~~1979~~TM, IEEE Standard Test Procedure for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis-~~(ANSI/DoD)~~.

IEEE Std C37.010-~~1979 (R1988)~~TM, IEEE Application Guide for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis-~~(ANSI)~~.

IEEE Std C37.011™, ~~1994~~, IEEE Application Guide for Transient Recovery Voltage for AC High-Voltage Circuit Breakers-~~rated on a Symmetrical Current Basis (ANSI)~~.

IEEE Std C37.012-~~1979 (R1988)~~TM, IEEE Application Guide for Capacitance Current Switching for AC High-Voltage [Circuit Breakers.](#)

[IEEE Std C37.013™, IEEE Standard for AC High-Voltage Generator](#) Circuit Breakers Rated on a Symmetrical Current Basis-~~(ANSI)~~.

[IEEE Std C37.015™, IEEE Guide for the Application of Shunt Reactor Switching.](#)

IEEE Std C37.016™, IEEE Standard for AC High-Voltage Circuit Switcher Rated 15.5 kV through 245 kV.

IEEE Std C37.11™, IEEE Standard Requirements for Electrical Control for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis.

IEEE Std C37.13™, IEEE Standard for Low-Voltage AC Power Circuit Breakers Used in Enclosures.

IEEE Std C37.14™, IEEE Standard for Low-Voltage DC Power Circuit Breakers Used in Enclosures.

IEEE Std C37.100-1992™, IEEE Standard Definitions for Power Switchgear-~~(ANSI)~~.

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³ ANSI publications are available from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (<http://www.ansi.org/>).

NOTE 1—Specific standards have been listed above; however, it must be recognized that circuit breakers have been manufactured and applied to power systems using standards of previous versions or editions. Requirements in standards have changed over time. Standards referenced for a failure investigation must be of the appropriate edition for the time when the circuit breaker was manufactured. The application standards used in the investigation must also be appropriate for the time when the circuit breaker was manufactured even though the circuit breaker may have been manufactured earlier than its installation on a power system.

NOTE 2—Some types of devices referred to as circuit breakers may have specific standards that are applicable to their design and/or installation. Examples are generator circuit breakers (IEEE Std C37.013) and circuit switchers (IEEE Std C37.016).

3. Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary: Glossary of Terms & Definitions* should be referenced for terms not defined in this clause.⁴

Report writers are encouraged to use the following definitions to promote consistent language in the report and to assist understanding by those reading the report.

3.1 ancillary equipment: Auxiliary or accessory equipment (e.g., thermometer, liquid level gauge, pressure gauge) (see also *The IEEE Standards Dictionary: Glossary of Terms & Definitions*).

3.2 circuit breaker unavailability: Time from the discovery of the failure until the breaker is ready to be returned to service.

3.3 contributing cause: A condition that contributes to the cause of the failure; however, may not of itself, result in failure. ~~A cause that, of itself, may not result in failure.~~

3.4 control circuit failure: Failure attributed to the inability of the electrical control circuit to perform its function.

3.5 defect: Imperfection in the state of an item (or inherent weakness) which can result in one or more failures of the item itself or of another item under the specific service or environmental or maintenance conditions for a stated period of time.

⁴ [The IEEE Standards Dictionary: Glossary of Terms & Definitions](http://shop.ieee.org/) is available at <http://shop.ieee.org/>.

3.6 diagnostic tests: Comparative tests or measurements of one or more of the characteristic parameters of a circuit breaker to verify that it performs its functions.

NOTE—The result from diagnostic tests can lead to the decision of carrying out overhaul.⁵

~~¹ANSI publications are available from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.~~

~~²IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.~~

~~³As this standard goes to press, IEEE Std 1325-1996 is approved but not yet published. The draft standard is, however, available from the IEEE. Anticipated publication date is December 1996. Contact the IEEE Standards Department at 1 (908) 562-3800 for status information.~~

3.7 electrical failure (of a circuit breaker): Failure attributable to the application of electrical stresses to the main circuit of the circuit-breaker.

3.8 examination: An inspection with the addition of partial dismantling, as required, supplemented by diagnostic tests in order to reliably evaluate the condition of the circuit breaker.

3.9 failure: Termination of the ability of an item to perform its required functions.

NOTE—The occurrence of a failure does not necessarily imply the presence of a defect if the stress is beyond that originally specified.

3.10 failure analysis: The logical, systematic examination of an item or its diagram(s) to identify and analyze the probability, causes, and consequences of potential and real failure. ~~(see IEEE Std 100-1992)~~ [\(See The IEEE Standards Dictionary: Glossary of Terms & Definitions.\)](#)

3.11 failure cause: The circumstances during design, manufacture, or use ~~which~~ [that](#) have led to failure. *Synonym:* **root cause**. ~~(see IEEE Std 100-1992)~~ [\(See The IEEE Standards Dictionary: Glossary of Terms & Definitions.\)](#)

3.12 failure detection: Examination to determine the position, evidence, and type of failure.

3.13 failure mode: The manner in which failure occurs; generally categorized as electrical, mechanical, thermal, and contamination.

3.14 failure modes and effects analysis (FMEA): [A process of identifying potential failures and their corresponding effects on the product or process under consideration—generally a design tool; however, it can also be used for failure analysis.](#)

3.15 focused tests: Tests performed to identify a particular area of failure.

3.16 forensic engineering: [Forensic engineering is the investigation of materials, products, structures or components that fail or do not operate or function as intended, causing personal injury or damage to property.](#) ~~The application of engineering knowledge to questions of law affecting life and property.~~

3.17 initiating cause: A cause that directly leads to the failure.

3.18 in-service inspection: ~~Visual periodic investigation~~ [Investigation](#) of the principal features of the circuit breaker in service, without dismantling. This investigation is generally directed toward pressures and/or levels of fluids, tightness, position of relays, pollution of insulating parts; however, actions such as lubricating, cleaning, washing, etc., that can be carried out with the circuit breaker in service are included.

NOTE—The observations resulting from inspection can lead to the decision of carrying out overhaul.

3.19 major failure (of a circuit breaker): Failure of a circuit breaker that causes the termination of one or more of its fundamental functions, which necessitates immediate action.

NOTE 1—A major failure will result in an immediate change in system operating condition; e.g., the backup protective equipment being required to remove the fault, or will result in mandatory removal from service for non-scheduled maintenance (intervention required within 30 min).

NOTE 2—CIGRE WG A3.0 defines a switchgear major failure as “failure of a switchgear and control gear which causes the cessation of one or more of its fundamental functions. A major failure will result in an immediate change in the system operating conditions, e.g., the backup protective equipment will be required to remove the fault, or will result in mandatory removal from service within 30 minutes for unscheduled maintenance.”

NOTE 3—IEC also provides a definition for a third failure type category: A defect is an “imperfection in the state of an item (or inherent weakness) which can result in one or more failures of the item itself or of another item under the specific service or environmental or maintenance conditions for a stated period of time.” Defects are, however, not included in the survey.

⁵ Notes in text, tables, and figures are given for information only and do not contain requirements needed to implement the standard.

3.20 mechanical failure (of a circuit breaker): Failure other than an electrical failure.

3.21 minor failure (of a circuit breaker): Any failure of a part or a sub-assembly that does not cause a major failure of a circuit breaker.

NOTE—CIGRE WG A3.06 defines minor failure as “failure of an equipment other than a major failure or any failure, even complete, of a constructional element or a sub-assembly which does not cause a major failure of the equipment.”

3.22 monitor: Continual or periodic ~~testing with comparison~~ collection of data in order to observe or determine trends.

3.23 overhaul: Work done with the objective of repairing or replacing parts that are found to be out of tolerance by inspection, or test, or examination, or as required by equipment maintenance manual, in order to restore the component and/or the circuit breaker to an acceptable condition.

3.24 operational failure: A failure where the circuit breaker fails to operate as intended when an operation is initiated.

3.25 repair: Work done to restore the component or the circuit breaker to condition for operation.

3.26 root cause failure analysis (RCFA): A method or series of actions taken to find out why a particular failure or problem exists and to correct those causes; investigative techniques applied to the determination of factors leading to the initiating or original failure.

3.27 servicing: Planned ~~servicing~~ maintenance or reconditioning of the circuit breaker including lubricating and replacing minor parts.

3.28 trending: The comparison of monitored data to determine or plan maintenance tasks and/or equipment replacement.

Part I ~~Failure investigation~~

4. Procedure for ~~the~~ investigation of circuit breaker failures

4.1 Determining the hazards and risks associated with the circuit breaker inspection

Electrical hazards must be considered during the circuit breaker failure investigation. Some components adjacent to the circuit breaker under investigation, as well as the parts of the control and protection circuits could remain energized or become energized during the investigation.

Appropriate isolation and temporary protective grounding must be established prior to the investigation. Proper personal protection should be selected and used based on the company safety policies and/or results of the arc-flash studies.

The failure of any electrical equipment could result in some level of hazardous material in, on, or around the circuit breaker site. These materials may be visible [such as an ash or discoloration of component(s)] or may be invisible products.

One must recognize that arc deposited residue may contain material that is hazardous to those working in and around the failed component(s). It is generally not possible to visually determine whether health hazards are present.

A first level assumption must be made that the materials in and around the failure are hazardous until clarification and classification has been confirmed, generally from the manufacturer. If the equipment vendor cannot provide verification of the material content, you should arrange for the material to be sampled and identified by a specialist before anyone is exposed.

Many workplace health and safety regulations apply in general (including OHSA, NFPA 70E, IEEE Std 1584, and NESC C2 in the USA). Follow company procedures and practices. Use personal protective equipment (PPE) that is appropriate to the worksite and conditions.

In addition, the following discussion describes some of the possible hazards.

Some older circuit breakers incorporated arc chute designs that contained asbestos and that may also include levels of radon. The percentage content of these two materials varied from one manufacturer to the next. Some early models of power circuit breakers also incorporated mercury-filled switches in the circuit breaker cell design. Some older oil-filled circuit breakers may contain oil with polychlorinated biphenyl (PCB). Asbestos, mercury, and PCB are materials known to be hazardous to humans. A high degree of expertise is required to safely execute the environmental requirements for a safe investigation.

Arc chutes were often constructed with some proportion of asbestos to resist the high temperatures of the electrical arc. Although tightly bound to the base material and not easily released to the atmosphere, (known as “non friable” asbestos) if these types of arc chutes are severely abraded, they may release dust that can become a hazard. When disturbed, flaking occurs resulting in airborne particles. A failure of a circuit breaker containing asbestos will distribute a certain level of airborne and residual contamination. While asbestos has been banned by the environmental protection agencies for most countries, electrical equipment containing asbestos has been and continues to be in service even after more than 40 years. A similar hazard can exist with asbestos wiring if it is shredded in the failure process.

More recently, high-voltage circuit breakers utilize Sulfur Hexafluoride (SF₆) gas as the insulation and interruption medium. SF₆ is heavier than air and will not support life. Because SF₆ is heavier than air, SF₆ gas can accumulate or be trapped in low “pockets.” There can be a risk of asphyxiation and inhalation of toxic gases when SF₆ is released in an indoor substation. If released into the atmosphere, precautions should be observed in nearby trenches, depressions, and

other locations where the gas can accumulate for short periods of time before dispersing into the atmosphere. Any tank previously containing SF₆ should not be entered without thorough ventilation and checks for suitable breathing atmosphere. Arced SF₆ gas is initially accompanied by a strong and irritating odor indicating toxic decomposition products. These products are injurious and exposure to them should be avoided. The arc byproduct powders are reactive with moisture and, if inhaled, could cause irritation in the nose, throat, and lungs. Contact with body perspiration could cause skin irritation.

Most HV circuit breakers contain some form of stored energy to allow opening and sometimes reclosing. This stored energy can take the form of springs, pneumatic, hydraulic systems, and magnetic actuated mechanisms or some combination of them. A circuit breaker may fail without discharging some or all of the stored energy. Special procedures are generally required to discharge the stored energy.

Broken porcelain or other materials can be very sharp and may have been projected some considerable distance from the circuit breaker.

Debris may have been projected to heights above the circuit breaker installation area. The site should be inspected for debris that has been projected to height and not yet fallen back to ground level.

Sometimes the worksite will be at an elevated height. Use appropriate fall prevention and fall arrest facilities.

Remember that some of those participating in the failure investigation may not be familiar with all of the possible hazards.

Make sure the worksite is safe.

Refer also to 4.3 for immediate action after a circuit breaker failure.

4.2 Classification of failures

A failure investigation should begin by determining whether the failure was a major failure, operational, or minor in order to decide what course of action to follow.

Refer also to preparations and training recommendations in Clause 4.

- a) Major failures. A large failure of the circuit breaker in which physical damage has occurred to power current carrying, power current interrupting, or high-voltage isolating elements. Major failures require the following:
 - 1) Exercise of extreme caution to minimize risk to personnel and other system equipment
 - 2) Collection of physical data and photos to aid in analyzing the failure
 - 3) Clean-up, repair or removal, and replacement of the failed circuit breaker to restore service
- b) Operational failures. A failure of the circuit breaker in which a lack of basic function occurs such as, a change of state occurs when not commanded, a change of state does not occur when commanded, the circuit breaker is locked in position due to a lack of some critical parameter, or an alarm is activated to warn of impending lack of basic function. An operational failure requires the following:
 - 1) Caution to determine whether it is appropriate to approach the circuit breaker
 - 2) Checking or troubleshooting features to diagnose the source of the failure
 - 3) Repair of the circuit breaker to restore service
- c) Minor failures. A minor failure requires the following:
 - 1) Checking or troubleshooting features to diagnose the source of the failure
 - 2) Repair or scheduling of repairs to the circuit breaker to prevent future lack of function

For major failures, the local personnel should be adequately trained to deal with immediate

hazards, isolation, grounding, etc. These personnel will likely not be in charge of the investigation of the failure. Therefore, although 4.2 through 4.6 describe what needs to be done, an organization should decide who will be trained to perform the actions at the scene required to preserve evidence, such as those listed in item a), b), d), and e) in 4.2, as well as contacting the appropriate internal group who will organize or lead the formal investigation. There may be a separate protocol for different levels of investigation, depending on the nature and initially perceived severity of the failure.

The user and manufacturer are very much encouraged to agree on the approach to evaluating the failure. Identify the prime reason for the investigation—e.g., is the prime importance to find the root cause of the failure or is it to repair the circuit breaker and return it to service? The method of investigation and disassembly could be quite different under these two scenarios.

~~A failure investigation shall begin by determining if the failure was catastrophic, operational, or minor in order to decide what course of action to follow.~~

~~a) *Catastrophic failures.* A failure of the circuit breaker in which physical damage has occurred to power current carrying or high voltage isolating elements. Catastrophic failures require~~

~~Exercise of extreme caution to minimize risk to personnel and other system equipment~~

~~Collection of physical data and photos to aid in analyzing the failure~~

~~Clean-up, and repair or removal and replacement of the failed circuit breaker to restore service~~

~~b) *Operational failures.* A failure of the circuit breaker in which a lack of basic function occurs such as, a change of state occurs when not commanded, a change of state does not occur when commanded, the circuit breaker is locked in position due to a lack of some critical parameter or an alarm is activated to warn of impending lack of basic function. An operational failure requires~~

~~Caution to determine if it is safe to approach the circuit breaker~~

~~Checking of troubleshooting features to diagnose the source of the failure~~

~~Repair of the circuit breaker to restore service~~

e) *Minor failures.* A minor failure requires

~~Checking of troubleshooting features to diagnose the source of the failure~~

~~Repair or scheduling of repairs of the circuit breaker to prevent future lack of function~~

4.3 Immediate action

- a) If there has been any personnel injury and/or continuing fire, call for medical emergency help.
- b) Provide first aid as needed.
- c) Evacuate the immediate area.
- d) Electrically, pneumatically, etc. isolate failed equipment as dictated by equipment condition.
- e) Do not try to operate failed equipment. Isolate from high-voltage sources. Before removing auxiliary power, verify status of all relay targets [and collect volatile memory if possible](#).
- f) Extinguish fire with caution or let it burn out. Cold water on hot porcelain can cause it to fracture. Prevent fire from spreading.
- g) Be aware of hazards of arced SF₆ gas and by-products, ~~PCBs~~ [polychlorinated biphenyls \(PCB\)](#), asbestos, and other toxic materials that could be present.
- h) Secure the area. Wait a few minutes. Do not immediately approach failed equipment because there may be high pressures, voltage, charged springs, [or](#) excessive thermal, or mechanical stresses in the equipment.
- i) Visually inspect failed equipment from ~~a safe~~ [an appropriately distanced](#) location to assess the situation.
- j) Follow established ~~safe~~ [safety-related](#) working procedures for isolation, grounding, [arc-flash hazard assessment, selection of PPE](#), etc., and practices regarding environment protection and spill control, etc.

4.4 On-site data collection (major failures)

- a) Take good quality photographs of everything before any disassembly or moving of parts.
- b) Photographs that show an overview from all angles as well as photographs that show close-up details will assist in documenting visual evidence. It is recommended that photographers include some form of reference measurement in all close-up photos to provide a reference to size.
- c) If on-site disassembly is required, photograph each step, with ~~an~~ a photo title, information or photo number card appearing in the photo. A scale measure that appears in each photograph can assist with later measurements. Consider backup recording by video camera. ~~Tape-record~~ Record all observations.
- d) Determine the position of all relays, targets, and counter readings, and determine system pressures before removing control voltages, if possible. Photograph the position of all relays, targets, and counter readings, if possible.
- e) Interview observers or record their observations as soon as possible.
- f) Obtain station oscillograms, sequence of events, ~~and~~ station or operator logs, and fault recordings.
- g) Obtain samples of oil, gas, air, etc.
- ~~f) Call the manufacturer and determine if the manufacturer wishes to be represented during failure investigation. Determine if a consultant is required to assist in analysis of failure.~~
- ~~g) Think through a failure sequence first and then look at the evidence.~~
- ~~h) All parts should be saved until the investigation is complete. Avoid a hasty cleanup.~~
- ~~i) Determine events immediately preceding, immediately succeeding, and simultaneous with failure.~~
- ~~j) Acquire/review manufacturer's engineering information, drawings, and test reports on other "special releases/reports."~~
- ~~k) Investigate each subsystem thoroughly (tripping subsystem including latch energy sources, linkages, etc.; main current contact path and movement, arcing contacts, nozzles, etc.; fluid subsystems (gas, air, and liquid); (i.e. investigation on a system and subsystem~~

~~basis).~~

- h) Record weather and other environmental conditions.
- i) Record electric system conditions and system operations/changes at, or just prior to, the event.
- j) If a failure was explosive, determine locations of expelled parts, distances parts traveled, sizes of parts, which parts, etc. Map the location of exploded/propelled items. Inspect parts for arc, wear, distortion marks etc. before beginning clean up, etc. Make photographs, videos, drawings, etc. as appropriate.
- k) Record the above data in the Circuit Breaker Reporting Form in Annex A.

4.5 Investigation

Refer to preparations and training in Clause 4.

- a) Contact the manufacturer and determine if the manufacturer wishes to be represented during failure investigation. Determine if a consultant or other resources are required to assist in analysis of failure.
- b) Determine events immediately preceding, immediately succeeding, and concurrent with failure.
- c) Review maintenance records to see if there has been any recent or repeating type activity.
Often failures result from parts disturbed during maintenance procedure.
- d) Inspect circuit breaker (external). Look for sticking parts, arc marks, burning, eroded metal, molten metal, signs of excessive pressure, etc., leakage of fluids [smoke (gas) or oil (liquid)]. Document with photographs.
- e) Determine or clarify the position (where they were before and immediately after the event) of all operating mechanism parts including auxiliary switch contacts, props, latches, linkage, pressure switches, valves, and control power breakers. Disconnect supply source switches before releasing mechanism stored energy. Follow manufacturer's requirements regarding maintenance operations.

~~p) If a failure was explosive, determine distances parts travelled, sizes of parts, which parts, etc.~~

~~Map location of exploded/propelled items. Inspect parts for arc marks etc. before beginning clean up, etc. Make pictures, movies, videotapes, drawings, etc. as appropriate.~~

- f) Open breaker access panels, inspect internals, and disassemble as necessary. Try to avoid disassembly until experts arrive!
- g) Investigate each subsystem thoroughly [tripping subsystem including latch energy sources, linkages, etc.; main current contact path and movement, arcing contacts, nozzles, etc.; fluid subsystems (gas, air, and liquid)]; (i.e., investigation on a system and subsystem basis). A fault tree or FMEA can usually provide guidance regarding which systems and subsystems to investigate.
- h) If disassembly is required, photograph each step, with an information card appearing in the photo. Consider backup recording by video camera. Record all observations.
- i) All parts should be saved until the investigation is complete. Avoid a hasty cleanup.
- j) Acquire/review manufacturer's service advisories, engineering information, drawings, and test reports or other "special releases/reports."

4.6 Investigation flow chart

In many situations, it may be desirable to perform selected tests. Figure 1 has been developed as a guide to aid in the determination and investigation of a failure.

The two starting points for this flowchart are as follows:

- a) Circuit breaker failure.
- b) ~~Routine~~ Diagnostic tests that show deviation from past history. Routine tests cover such tests as those listed in Table 3.

The paths in the flowchart lead to scrapping or repairing and returning to service. Prior to returning to service, it may be desirable to perform selected tests to verify suitability for service.

Based upon the external observations (see Table 16) or the presence of obvious damage, selected tests may be performed as suggested in Table 17. From their results, a hypothesis of failure can be developed. This may be confirmed through internal inspection and teardown as deemed appropriate.

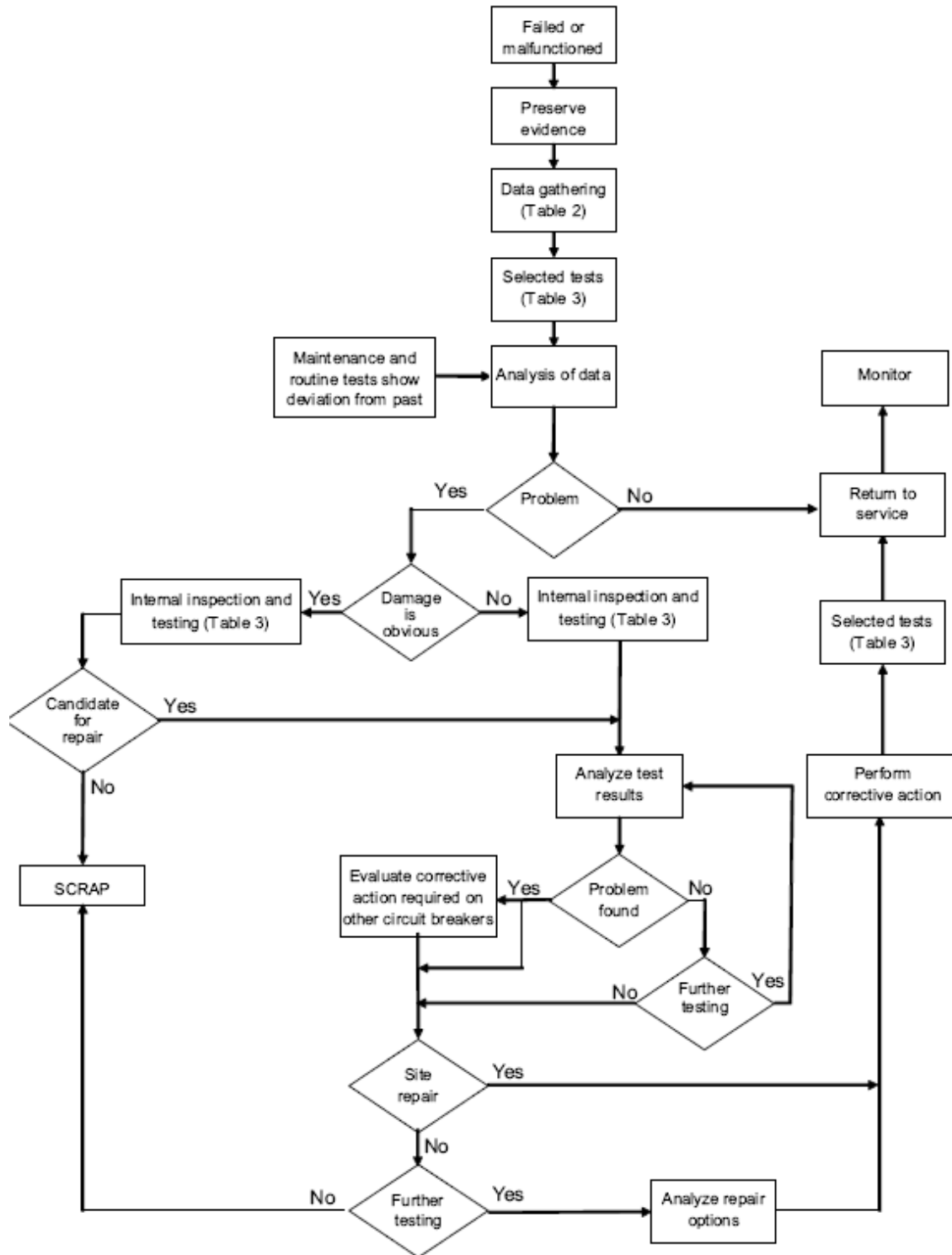


Figure 1—Flow chart of recommended investigation actions

4.7 Recommended plan of action

4.7.1 Failure investigation

- a) Determine if the circuit breaker was in a long-term static position or if it had recently changed state when the failure occurred or was initiated.
- b) If the failure was during a static position
 - 1) Determine where the initial ~~breakdown~~failure occurred.
 - 2) Determine whether the insulating fluid (gas or liquid) systems were fully charged and full.
 - 3) Determine whether the paths to ground were in specified condition, i.e., gas and air dry; minimum external contamination; no conducting paths to ground.
 - 4) Determine whether there were any voltage stresses that could have exceeded the nameplate levels, i.e., lightning, switching surges, or other transients.
 - 5) ~~Look at~~ Analyze maintenance records for ~~clues~~evidence as to the cause.
 - 6) If the breaker failed while open, check for condition of the grading capacitors that could cause unequal voltage distribution across the ~~breaks~~contacts.
 - 7) Determine if other system events occurred recently or at the time of failure.
- c) If the failure appeared to be initiated during fault interruption or opening operation.
 - 1) Read oscillographs and digital fault recordings if available.
 - 2) Determine whether the operating voltage and system short-circuit level was within the nameplate rating of the ~~switchgear~~circuit breaker.
 - 3) Determine whether the breaker has capability of switching capacitors if it was used for that purpose.
 - 4) Check the pressure interlocks for adjustment and proper functioning.
 - 5) Verify that all mechanisms are in the same position. Look for broken parts of mechanism or valve gear as well as for evidence of pumping if all mechanisms are not in the same

position.

- 6) If a circuit breaker opened and failed several seconds or minutes later, consider the possibility that it opened, dumped insulating fluid by a valve failure or other means, and then failed dielectrically.
 - 7) Determine whether there was any lightning [activity](#) in the vicinity. If so, consider the possibility that the circuit breaker was opening due to a lightning stroke or shield failure and failed due to a subsequent lightning stroke.
 - 8) Look at maintenance records for ~~evidence~~[evidence](#).
 - 9) Check condition of resistor switches, resistors, and grading capacitors for any malfunction that would cause unequal voltage distribution across the ~~breaks~~[contacts](#).
- d) If the failure appeared to be initiated during closing
- 1) Read oscillographs and digital fault recorders if available.
 - 2) Determine whether the system momentary current was within the nameplate rating of the circuit breaker.
 - 3) Determine whether the breaker was fully closed.
 - 4) Look at the maintenance records for ~~evidence~~[evidence](#).
- e) A review of the above results ~~will probably~~[should](#) give direction to the troubleshooting staff.

4.7.2 Review of circuit breaker application

- a) [Review the circuit breaker installation, operation, and maintenance manual to compare actual conditions and practices with installation, operation, and maintenance conditions and practices.](#)
- b) [Review manufacturer and owner circuit breaker drawings to verify that the circuit breaker has been installed according to its planned installation design.](#)
- c) [Refer to the appropriate edition of IEEE standards for circuit breaker ratings and testing. Refer to Annex B for a listing of some of the current and superseded switchgear standards.](#)
- d) [Refer to IEEE standards and guides for the application of circuit breakers, especially IEEE](#)

Std C37.06, ANSI C37.06.1, IEEE Std C37.010, IEEE Std C37.011, IEEE Std C37.012, IEEE Std C37.015, and IEEE Std C37.11, IEEE Std C37.13, and IEEE Std C37.14. These guides and standards contain information that may pertain to the specific application conditions where and when the circuit breaker was installed and should be used as a basis for verifying the power system and circuit breaker needs and capabilities. Refer to Annex B for a listing of some of the current and superseded switchgear guides.

- e) Refer to the original circuit breaker specification and technical documents provided by the manufacturer at the time of purchase and application.
- f) Verify that the appropriate editions or versions of the standards, to which the circuit breaker was manufactured and applied, are used for the investigation.
- g) Be aware that due to increased system fault contribution and/or operating voltage, an older circuit breaker may no longer be adequate for the existing application. A short circuit study should be made to determine if the circuit breaker is adequate to interrupt the fault current that was available at this circuit position at the time of the circuit breaker failure. Similarly, an insulation coordination study may be appropriate to determine if the circuit breaker had appropriate dielectric capabilities for the application at the time of the failure.

NOTE—A different short circuit study may be required to apply a replacement circuit breaker to this location. This short circuit study considers the future short circuit current that will be available for the replacement circuit breaker to interrupt well into the future.

4.7.3 Summarizing failure analysis

- a) In summarizing the failure analysis, indicate the sequence of events that caused the failure. If possible, give the time the events occurred and backup data.
- b) State the most probable cause of failure.
- c) State any corrective actions that may minimize the risk of future failure occurrences.
- d) The failure analysis should make use of terminology used in IEEE Std C37.100 and in Clause 3 of this guide.

4.7.4 Summary

- a) Gather data as described in Clause 6.
- b) Review records of oscillographs and operations, including weather, and any voltage and current transient information on system and related circuit breaker operations.
- c) Review existing application vs. ratings of the applied circuit breaker.
- d) Review maintenance records.
- e) Prepare sequence of events from the time all systems were normal until failure.
- f) Propose all possible failure sequences.
- g) Determine most likely cause by analyzing each possible failure sequence using the evidence collected.
- h) Inspect other identical type circuit breakers and determine if all parts are present, in similar condition to the failed circuit breaker and that no foreign parts are present.
- i) Determine if other similar equipment has had similar experiences, or could have similar failures in the future.
- j) Determine corrective action plan.
- k) Determine which parts are damaged and what damaged them.

Part II Diagnostics

Diagnostics

5. Diagnostic tests and advanced diagnostics

As an aid to diagnose the circuit breaker condition and to predict any impending failure, the user should consider monitoring the various circuit breaker features and functions.

Circuit breaker diagnostics will assist the user in predicting the working condition of the parts and in extending the maintenance intervals.

Circuit breakers can be furnished with some built-in monitors. Additional monitoring is possible. The quantity and complexity of additional monitoring will depend upon the type and rating of the circuit breaker, and its importance in the system and user's preferences.

Monitoring a circuit breaker requires some or all of the following actions on the part of the user:

- a) Periodic visual inspection and recording of indicators, marks, gauges, indicating lights, etc., at the circuit breaker location, without any dismantling, or de-energizing, but may require opening mechanism cabinet doors.
- b) Periodic visual inspection and recording of indicators and gauges, etc., at a remote location, without dismantling, de-energizing of the circuit breaker. This may require permanent connection of transducers, auxiliary contacts, etc.
- c) ~~Visual observation~~ Periodic visual inspection and recording of indicators, gauges, etc., temporarily connected to the circuit breaker, e.g., pressure gauges.
- d) Automatic recording, continuous or periodic at set intervals, of the circuit breaker's basic functions by using chart recorders, sequence of events recorder, fault monitors, etc. This may require the circuit breaker to be de-energized and partially dismantled or at least operated while in

service.

e) Installation of complex diagnostic systems, either permanently connected to each circuit breaker or as a plug-in device to be used periodically.

f) Diagnostic tests carried out externally, e.g., timing tests, contact resistance, insulation, power factor, etc.

This may require the circuit breaker to be de-energized and partially dismantled or at least operated while in service.

g) Inspection with de-energizing and partial dismantling, as required, supplemented by measurements, non-destructive tests, etc.

h) Analysis of pressure switches' settings and operation. This may require the circuit breaker to be de-energized. ~~See annex A for monitoring techniques and diagnostic systems.~~

Table 1 through Table 14 list some of the features and characteristics of the circuit breaker recommended for [testing or](#) monitoring. These tables include the following:

- Characteristic to be [tested or](#) monitored
- Circuit breaker operating mode for [testing or](#) monitoring
- Parameters measured and derived information
- Assessment of the circuit breaker condition based on the derived information

~~e) Typical benefit/effort analysis for a typical utility~~

Some of the characteristics are monitored continuously by means of gauges, mechanical indicators, or by means of relays, transducers, etc., connected to the circuit breaker control system. Remote indication is provided by transducers. Other characteristics require the circuit breaker to be de-energized and isolated or even dismantled.

Several characteristics such as power factor, resistances, etc., require the user to maintain records and observe the trend of the measured values for proper assessment of the circuit breaker condition.

NOTE—The following letter symbols apply to the Operating Mode column in Table 1 through Table 14.

I Circuit breaker energized and in service

O Circuit breaker de-energized and isolated

~~Effort to provide a monitoring system includes the cost of necessary materials, design, and labor effort required and the ongoing cost of operating and maintaining the system(s) and depends upon several factors such as the type of circuit breaker, complexity of the monitoring system, quantity of circuit breakers involved, and their location. Effort to provide a monitoring system will vary among users~~

~~Effort for the application of a monitoring system is defined as *Low* when the system can be provided without any significant design and labor effort on the part of the circuit breaker manufacturer or the user.~~

~~Effort for the application of a monitoring system is defined as *Medium* when it was judged that the design and labor effort was somewhere between *High* and *Low*.~~

~~Effort for the application of a monitoring system is defined as *High* when the system requires a substantial design and labor effort, or if it requires the circuit breaker to be de-energized or partially disassembled. Cost is also considered to be high when the information obtained could have been indirectly derived from some other low cost system.~~

~~Effort for the application of a monitoring system is defined as *Extremely High* if circuit breaker must be moved to another location for test or elaborate field setup must be made.~~

~~Benefit is defined as *Low* when the derived information is essentially for statistics or to determine or observe trends, or it detects a condition that does not require an immediate action on the part of a~~

user.

Benefit is defined as *Medium* when the derived information is judged to be somewhere between *High* and *Low*. Benefit is considered as *High* when the derived information indicates a situation which, if not corrected, can lead to a major failure of the circuit breaker.

Note that the benefit vs. effort analysis shown in these tables is for a typical utility with a variety of circuit breakers, well-established maintenance practices and a centralized control, and may not apply to all users.

The user should perform his own analysis and determine the extent to which circuit breakers should be equipped with the monitoring devices. The manufacturer may provide recommendations pertaining to monitored parameters.

A knowledge of historical reported failure modes together with the importance of the circuit breaker(s) on the particular system will assist the users in assigning value—Benefit/Effort—for the monitoring system desirable for their needs.

Table 1—Diagnostics of all types of circuit breakers (mechanical features)

Characteristics to be assessed (from tests and/or monitors)	Operating mode	Parameter measured and derived information	Assessment
Indicator status vs. mechanism position	I	Compare open/closed status indicators vs. mechanism position	Integrity of mechanism, linkages, latches, and indicators to move main contacts to open/closed status position correctly indicate position
Main contact status vs. trip close commands	O	Time from coil energization to main contact make or break	Operation of trip coil, close coil, mechanism during open and close
Contact (main, resistor switch, auxiliary switch) position vs. time	O	Contact displacement and contact continuity vs. time	Strength of stored energy system; adequacy of lubrication damper operation, contact bounce, mechanism friction, and adequate contact engagement
Auxiliary contact status vs. trip close command	I	Time from coil energization to auxiliary contact make or break	Operation of trip coil, close coil, mechanism during close/open operation
Condition of latch devices	O	Determine the proper operation of latch devices	Time required to operate trip or close latch indicates condition of latch system

Table 2—Diagnostics of all types of circuit breakers (electrical current carrying features)

Characteristics to be assessed (from tests and/or monitors)	Operating mode	Parameter measured and derived information	Assessment
Contact resistance	O	Resistance in $\mu\Omega$ of contacts and other parts of current path	Contact surfaces joint integrity and applied forces
Integrity of electrical joints	O	Connections temperature measurements	Contact and terminal condition
Bushing terminal temperature	I	Relative temperature of bushing terminal	Bushing terminal temperature within specification at a given reference current loading level Condition of bushing terminal

Table 3—Diagnostics of all types of circuit breakers (electrical insulating features)

Characteristics to be assessed (from tests and/or monitors)	Operating mode	Parameter measured and derived information	Assessment
Voltage withstand of insulation (High-voltage withstand tests are difficult to perform in the field.)	O	Voltage withstand or breakdown at no less than specified voltage	Find contaminated or otherwise inadequate line-to-line and line-to-ground insulation
Interrupter voltage withstand (High-voltage withstand tests are difficult to perform in the field.)	O	Voltage withstand or breakdown at no less than specified voltage	Find contaminated interrupter insulation and grading capacitor insulation
Audible noise	I	Unusual audible noise, corona, or vibration present	Identifies deterioration or degradation of the insulating paths
External corona test Partial discharge test (performed in a plant or laboratory with acceptable low background PD level)	O	Corona present	Insulation deterioration Contacts damaged or not touching
Leakage current, power factor and capacitance of the breaker	O	Capacitance, leakage current, and power factor of entire breaker from all primary terminals to ground (leakage current and insulation power factor may be a function of bushing surface contamination)	Capability of bushing insulation to withstand specified voltage Quality of bushing insulation Integrity of all line-to-ground insulation systems

Table 4—Diagnostics of all types of circuit breakers (auxiliary and control circuits)

Characteristics to be assessed (from tests and/or monitors)	Operating mode	Parameter measured and derived information	Assessment
Closing power source and tripping power of source, recharging power source, heater power source	I	Voltage of sources	Adequacy of sources to supply closing and tripping power and to charge stored energy devices (pneumatic, hydraulic or spring) and power to heaters (if present)
Trip and close coil operation	O, I	Coil current magnitude and shape during operation	Integrity of coils, auxiliary switch contacts and wiring, plus capability of power source
Motor operation	I	Stored energy device; current drawn from source on operation	Integrity of motors, auxiliary switch contacts and wiring, plus capability of power source
Heater operation	I	Heater current drawn from source on operation	Integrity of heaters, wiring, and capability of power of source
Remote control operation	O, I	Remote controls produce desired operational results	Integrity and position of local/remote switch, wiring and communication channels
Control circuit function	O	Determine that the control circuit functions in the manner intended	Control circuit is functioning correctly

Table 5—Diagnostics of all types of circuit breakers (Interrupter)

Characteristics to be assessed (from tests and/or monitors)	Operating Mode	Parameter measured and derived information	Assessment
Interrupter performance	O	Current and contact travel during switching operation	Integrity of interrupter, linkages and mechanism to interrupt current and open the power circuit
Interrupter usage	O	Arc energy accumulated or amount of contacts eroded based on adjusted interrupted amperes ($I^n t$) where n is dependent on type of contact	Interrupter life expended or remaining

Table 6—Diagnostics of circuit breakers (special features of metal-clad circuit breakers)

Characteristics to be assessed (from tests and/or monitors)	Operating mode	Parameter measured and derived information	Assessment
Mechanical inter- lock function	O	Circuit breaker open/closed status or change of status vs. circuit breaker position in cubicle	Prevention of closed circuit breaker from engaging or disengaging primary disconnects. Prevention of circuit breaker with charged springs from being withdrawn from cubicle
Breaker/switchgear rating installation Interference features	O	Breaker rating compared to switchgear cubical rating	Presence and proper operation of insertion interference features to prevent circuit breaker of one rating from being installed in a different rated switchgear cubicle

Table 7—Diagnostics of circuit breakers (special features of air magnetic circuit breakers)

Characteristics to be assessed (from tests and/or monitors)	Operating mode	Parameter measured and derived information	Assessment
Arc chute	O	Physical and magnetic properties of arc chute	Verify the integrity of all arc chute parts to control the arc by physical and/or magnetic means
Puffer	O	Air flow rate and volume on open operation and on open strokes of close/open operation	Proper operation of puffer to produce an air flow to interrupt the arc at low currents
Cooling fans (if present)	I	Operation, air flow	Adequacy of cooling

Table 8—Diagnostics of circuit breakers (special features of vacuum circuit breakers)

Characteristics to be assessed (from tests and/or monitors)	Operating mode	Parameter measured and derived information	Assessment
Vacuum interrupter	O	Voltage withstand or breakdown at no less than specified voltage	Adequacy of vacuum, open gap dimensions, contact characteristics required to successfully withstand specified voltage and interrupt arcs
Contact condition	O	Main contact wear dimension	Change in contact dimension, contact gap, contact life, contact wear, closing and over-travel
Cooling fans (if present)	I	Operation, air flow	Adequacy of cooling

Table 9—Diagnostics of circuit breakers (special features of bulk oil circuit breakers)

Characteristics to be assessed (from tests and/or monitors)	Operating mode	Parameter measured and derived information	Assessment
Oil volume	I	Level of oil in tank, Level of oil in bushings	Verify that enough oil is present
Oil quality	I	Oil power factor, Oil particle type and count, Dissolved and free water in oil, Withstand voltage of oil	Presence of proper oil quality required to successfully withstand voltage and interrupt arcs
Closing (opening) resistors (if present)	O	Resistance in Ω	Determine if resistance is within tolerance
	O	Insertion time in ms	Determine if insertion time between resistor switch closing (opening) and main contact closing (opening) is within tolerance
Current-carrying capacity Grading resistor (if present)	I, O	Oil level, Tank temperature	Determines indirectly the ability of the circuit breaker to carry load current
	O	Varnish or carbon on contacts	Determine indirectly the ability of the circuit breaker to carry load current
	O	Resistance in Ω	Determine if resistance is within tolerance
Bushing condition	O	Power factor and capacitance	Verify correct values within tolerance
Grading capacitors (if present)	O	Capacitance in pF	Determine if capacitance is within tolerance